pipe **60** has an ultrasonic transmitter **62** attached to one end thereof. An ultrasonic receiver **64** and an accelerometer **66** is coupled to the pipe. A shaker **68** is also coupled to the pipe. The shaker **68** is driven by signal generator **70** and a power amplifier **72**. The ultrasonic transmitter **62** is driven by signal generator **71** and power amplifier **73**. In practicing the method of this invention, the ultrasonic transmitter **62** generates the high frequency signal and the shaker **68** provides the low frequency signal. The receiver **64** is coupled to data acquisition system **74** via a high pass filter **76**. The accelerometer **66** is coupled to the data acquisition system **74** via a low pass filter **78**.

FIG. **8***a* shows a series of 50 μs bursts with the carrier frequency near 1 MHz received from the sample. The frequency of repetition is 1600 Hz. The frequency of applied vibration is 494 Hz. As shown in FIG. *8a,* the received waveform has signals reflected from both flanges. FIG. **8***b* and FIG. **8***c* shown the selected burst reflected from the defective and the defect-free flanges. FIG. **9***a* shows the spectra of the entire waveform. FIGS. **9***b* and **9***c* show the spectra of corresponding selected sequences of the bursts reflected from the flange containing the defect. These spectra demonstrate the presence of the modulation in the sequence of the bursts reflected from the flange containing a defect (FIG. 9*c*). No modulation of the sequence of bursts reflected from the defect-free flange is shown.

The method of the present invention also enables defects to be quantitatively analyzed. The frequency of the high frequency signal is swept over a defined frequency range and the amplitudes of the side bands are measured, averaged, and normalized in accordance with the following equation: M=Am/ApAv where Am is the amplitude of the side band signal, AP is the in amplitude of the high frequency signal and Av. is the amplitude of the low frequency signal. The resulting number, M, indicates the size of the defect. The number of steps in the frequency range selected is typically 10–20. The range of frequency over which the measurements are taken is typically 10–30 kHz.

The present invention also relates to the nondestructive detection of ice on solid surfaces such as aircraft wings, road pavements, etc. The interface between the ice and the structure, for the purposes of this invention, can be considered a defect. When used in this manner, ultrasonic probing signals and low frequency vibration signals are applied to a structure to detect ice. The low frequency vibration signals could be either generated in the structure or already present in the structure by operations involving the structure. These operations may include vibrations from an engine or low frequency signals due to turbulence. The vibrations may also be present in a structure due to the environment as by traffic or the wind.

In a structure without ice cover, the ultrasonic probe signal and the low frequency vibration signal propagate independently without any interaction. If the structure is covered with ice, there is significant interaction between the ultrasonic probe signal and the low frequency vibration. The ultrasonic probe signal is modulated by the low frequency vibration signal. In the frequency domain, the modulation appears as sideband spectral components with respect to the frequency of the ultrasonic probe signal. These sideband spectral components are considered as new signals associated with the presence of ice, so that the ice can be more easily detected when such signals are observed.

Ice may be detected in aircraft, road pavement, bridges, etc. using this method. Ultrasonic and vibration signals are applied to and received from the inspected structure in the area of interest. The method may operate to detect the presence or absence of ice. The method may also operate in a localized manner to locate the iced area using burst signals and the described above signal-processing algorithm.

The modulation method of the present invention has a number of advantages over acoustic techniques used in the prior art. In the prior art linear techniques, variation of linear acoustic parameters, which indicate the presence of ice, may depend on other factors such as temperature changes or structural load. These other factors cause a similar or greater effect on the measured parameters than the presence of ice. The modulation method of the present invention is not affected by these factors, as they do not cause modulation of the probe signal.

The method of this aspect of the present invention can be implemented on an aircraft wing is shown in FIG. **10**. Aircraft wing **80** is connected to an aircraft body **81**. The wing **80** has ultrasonic transmitter **82** and an ultrasonic receiver **84** embedded therein. A source of low frequency vibrations such as aircraft engine **86** is also attached to the wing **80**. A digital signal processing system **88** is connected to signal generator **90**, which is in turn connected to a power amplifier **92** for generating the transmitted signal. The processing system **88** is also connected to receiver **84** via a signal-conditioning device **94**.

FIGS. **11***a* and **11***b* show the spectra of received signals from an aluminum plate that was placed within a freezer. Two identical piezoceramic disks (ultrasonic transmitter and receiver) were glued to the plate. The vibration signal was generated with a hammer. The modulation was monitored before and after spraying water on the plate. A dramatic increase in modulation occurred even with only a small area of ice (10%). The spectrum of the received signal from the plate without ice is shown in FIG. **11***b*. The spectrum of the received signal from the plate with 10% of its area covered with ice is shown in FIG. **11**(*b*). The presence of ice increases the amplitude of the side-band components of the received signal up to 20 dB.

Having thus described the invention in detail, it is to be understood that the foregoing description is not intended to limit the spirit and scope thereof. What is desired to be protected by Letters Patent is set forth in the appended claims.

What is claimed is:

1. An apparatus for detecting the presence and characteristics of a defect in or ice on a structure comprising:

means for creating and delivering a low frequency signal to the structure;

means for creating and delivering a high frequency probe signal to the structure; and

receiver means for receiving a modulated signal from the structure caused by the low frequency signal modulating the high frequency signal in response to a defect in or ice on the structure, the modulated signal indicating the presence of a defect in or ice on the structure.

2. The apparatus of claim **1** further comprising means for moving the low frequency signal relative to the high frequency probe signal and receiver means; and means for triggering the probe signal after the low frequency signal to locate a defect in the structure.

3. A method of detecting the presence and characteristics of a defect in or ice on a structure comprising the steps of:

applying a low frequency signal to the tested structure;

applying a high frequency probe signal to the tested structure;

modulating the high frequency signal by the low frequency signal in response to the presence of a defect in the structure; and

receiving a modulated signal through a receiver means applied to the tested structure.

4. The method of claim 3 further comprising locating the defect in the structure by triggering the probe signal to occur immediately after the low frequency signal is applied to the tested structure; moving a point of delivery of the low frequency signal about the tested structure; and monitoring the amplitude of the modulated signal for increased modulation.

5. A method for detecting the presence and characteristics of a defect in or ice on a structure comprising the steps of:

propagating an ultrasonic probe signal in the structure;

propagating a low frequency vibration signal in the structure;

detecting said ultrasonic probe signal and analyzing said detected ultrasonic probe signal for interaction between said ultrasonic probe signal and said low frequency vibration signal caused by a defect in or ice on the structure, said interaction being indicative of a defect in or ice on the structure.

6. The method of claim 5 wherein said interaction is a modulation of said ultrasonic probe signal by said low frequency vibration signal.

7. The method of claim 6 wherein said modulation appears as sideband spectral components with respect to a frequency of said ultrasonic probe signal.

8. The method of claim 7 wherein said sideband spectral components are associated with the presence of a defect in or ice on the structure.

9. The method of claim 6 wherein said low frequency signal exists in said structure because of the operation or the environment of the structure.

10. A method of determining the location and characteristics of defects in or ice on a structure comprising the steps of:

propagating sequences of an ultrasonic probe signal in a structure;

said ultrasonic probe signal having a first frequency;

said sequences being propagated at a second repetition frequency;

propagating a low frequency vibration signal in said structure the low frequency vibration signal modulating the ultrasonic probe signal in response to a defect in or ice on the structure;

detecting said propagated sequences of the probe signal, and selecting and processing only propagated sequences which are indicative of an area of said structure having a defect or ice.

11. The method of claim 10 wherein said second repetition frequency is sufficiently short to be resolved from the ultrasonic probe signal reflected from the other areas of said structure.

12. The method of claim 11 wherein said second repetition frequency is greater than twice the frequency of said low frequency vibration signal.

13. An apparatus for non-destructive testing of a structure comprising:

means for transmitting an ultrasonic signal into said structure;

means connected to said structure for receiving said ultrasonic signal;

means connected to said structure for generating a low frequency signal in said structure; and

control means connected to said transmitting means and to said low frequency generating means for transmitting said ultrasonic signal into said structure at a repetition frequency which is greater than twice the frequency of said low frequency signal;

wherein, the low frequency signal modulates the ultrasonic signal in response to a defect in the structure.

14. The apparatus of claim 13 wherein said low frequency signal is generated from the operation or the environment of said structure.

15. An apparatus for determining the location and characteristics of defects in ice on a structure comprising:

means for generating a low frequency signal in a structure;

means for generating a high frequency signal in the structure;

means for receiving a modulated signal from the structure caused by said low frequency signal modulating said high frequency signal in response to a defect in or ice on the structure; and

means for analyzing side bands in said received signal for analyzing a defect or ice.

16. The apparatus of claim 15 wherein said means for generating a low frequency signal includes a shaker.

17. The apparatus of claim 15 wherein said means for generating a low frequency signal includes an instrumented hammer.

18. The apparatus of claim 15 wherein said means for generating a low frequency signal includes vibrations present in the structure due to environment and/or working conditions.

19. An apparatus for quantitatively analyzing defects in a structure comprising:

means for generating a high frequency signal in a structure;

means connected to said high frequency signal generating means for varying the frequency of said high frequency signal over a predetermined frequency range;

means for generating a low frequency signal in said structure;

means for receiving frequency modulated signals from said structure caused by the low frequency signal modulating the high frequency signal in response to a defect in the structure, said received modulated signals being indicative of a defect in said structure; and

means connected to said receiving means for measuring, averaging and normalizing the amplitudes of side bands in said received modulated signals to generate an indication of the size of a defect in the structure.

20. The apparatus of claim 15 further comprising:

means for moving location of said low frequency generating means on said structure relative to the location of said means for generating said high frequency signal; and

control means for triggering said high frequency signal after said low frequency signal is triggered, whereby the amplitude of said side bands is increased as the location of said low frequency signal generating means is moved towards a defect.

21. An apparatus for locating defects in structures comprising:

means for generating a low frequency signal in a structure;

means for generating sequences of a short burst high frequency signal in the structure;

means for receiving a signal from the structure, said signal being a modulated combination of said low frequency signal and said high frequency signal;

means for analyzing selected sequences of said received signal from areas of the structure;

whereby a presence of modulation in a selected sequence indicates the presence of a defect in an area of the structure.

22. The apparatus of claim 1 wherein the means for delivering a signal comprises an ultrasonic transmitter and the means for receiving a signal comprises an ultrasonic receiver.

23. The apparatus of claim 22, wherein the structure comprises an aircraft wing and the transmitter and receiver are embedded in the wing.

24. The apparatus of claim 22 wherein the transmitter and receiver comprise piezoceramic material.

25. The method of claim 4 wherein modulation of the modulated signal appears as side-band components in the spectrum of the high frequency signal, and the step of monitoring the amplitude of the modulated signal comprises monitoring the amplitude of the side-band components in the spectrum of the high frequency signal.

26. The method of claim 3 wherein the low frequency signal comprises harmonic vibration.

27. The method of claim 26 wherein the harmonic vibration is applied by a shaker.

28. The method of claim 3 wherein the low frequency signal comprises impact modulation.

29. The method of claim 28 wherein the impact modulation is applied with an instrumented hammer.

30. The method of claim 3 wherein the low frequency signal comprises self-modulation.

31. The method of claim 30 wherein the self-modulation is applied by the environment.

32. The method of claim 30 wherein the self-modulation is applied by working conditions.

33. A method of analyzing defects in a structure comprising:

generating a high frequency signal in a structure;

sweeping the frequency of the high frequency signal over a frequency range;

generating a low frequency signal in the structure;

receiving modulated signals caused by the low frequency signal modulating the high frequency signal in response to a defect in the structure; and

analyzing side bands of the modulated signals to analyze the defect.

34. The method of claim 33 wherein the step of analyzing the side bands of the modulated signal comprises measuring, averaging, and normalizing amplitudes of the side bands.

35. The method of claim 34 wherein the size of the defect is derived by dividing the amplitude of the side bands by the product of the amplitude of the high frequency signal and the amplitude of the low frequency signal.

36. The method of claim 33 wherein the frequency range has 10 to 20 steps.

37. The method of claim 33 wherein the frequency range comprises 10–30 kHz.

38. A method for locating defects in a structure comprising:

generating a low frequency signal in a structure;

generating sequences of a short burst high frequency signal in the structure;

receiving a modulated signal from the structure caused by the low frequency signal modulating the high frequency signal in response to a defect in the structure;

analyzing modulation of sequences of the received signal from areas of the structure to locate a defect in the structure.

39. The apparatus of claim 21 wherein the means for receiving a signal from the structure comprises an array of receivers.

* * * * *